

First ground-based CCD proper motions for Fornax II: Final results

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ABSTRACT

We present the first entirely ground-based astrometric determination of the proper motion for the Fornax Local Group Dwarf Spheroidal satellite galaxy of the Milky Way, using CCD data acquired with the ESO 3.5 m NTT telescope at La Silla Observatory in Chile. Our unweighted mean from five Quasar fields in the background of Fornax, used as fiducial reference points, leads to $\mu_\alpha \cos \delta = 0.62 \pm 0.16$ mas y^{-1} , and $\mu_\delta = -0.53 \pm 0.15$ mas y^{-1} . A detailed comparison with all previous measurements of this quantity seems to imply that there is still no convincing convergence to a single value, perhaps indicating the existence of unaccounted systematic effects in (some of) these measurements. From all available proper motion and radial velocity measurements for Fornax, we compute Fornax's orbital parameters and their uncertainty using a realistic Galactic potential and a Monte Carlo simulation. Properties of the derived orbits are then compared to main star formation episodes in the history of Fornax.

All published proper motion values imply that Fornax has recently (200-300 Myr ago) approached perigalacticon at a distance of ~ 150 kpc. However, the derived period exhibits a large scatter, as does the apogalacticon. Our orbit, being the most energetic, implies a very large apogalactic distance of ~ 950 kpc. If this were the case, then Fornax would be a representative of an hypervelocity MW satellite in late infall.

Subject headings: Astrometry: Proper motions — Galaxies: Local group — Galaxies: Dwarf spheroidal galaxies — Galaxies: Fornax — Galaxies: Proper motion — Stars: proper motions

1. Introduction

Studying the kinematics of the satellites of the Milky Way (MW) allows us to address various fundamental issues such as the origin and evolution of this satellite system (and the MW itself), the role of tidal interactions in the evolution of the Local Group (LG) and the matter distribution of the latter (including that of the dark matter, thus allowing tests of some cosmological predictions (Shaya et al. 2009)). This requires tracing their positions back in time, by integrating their orbits, which, in turn, requires knowing their current positions and their full 3-D space velocities. While radial velocities for LG galaxies are known to better than $\sim 5 \text{ km s}^{-1}$, and their distances to $\sim 10\%$, the biggest source of uncertainty rests on their proper motions (PMs).

In the year 2000 we started a ground-based program aimed at determining the absolute PM of three southern dwarf Spheroidal (dSph) galaxies, Carina, Fornax and Sculptor, with respect to background Quasars (QSOs), used as inertial reference points. Three to four epochs of homogeneous CCD data were obtained using a single telescope+detector setup over a period of eight years: Ours is the first entirely optical CCD/ground-based PM study of an external galaxy other than the Magellanic Clouds.

In Méndez et al. (2010, hereafter Paper I), we presented a detailed description of our methods, as well as our first results for the PM of Fornax, based on one QSO field (QJ0240-3434B). In this paper we present our final PM for Fornax based on measurements from five QSO fields in the background of Fornax. In Section 2 we present a summary description of our observational material, in Section 3 we explain how we obtained our PMs, and, finally, in Section 3.1 we compare our results to previous studies and present our main conclusions.

The Fornax dSph galaxy, at a distance of 147 kpc (e.g., Pietrzyński et al. 2009), is relatively isolated, luminous and well-resolved into individual stars. It seems to be dark matter dominated, and has an estimated total mass of $\sim 10^9 M_\odot$ (e.g., Walker et al. 2007). Unlike other dwarf galaxies, Fornax harbours five globular clusters (Hodge

1961)¹, and it appears to have a complex stellar substructure in the form of shell-like features indicative of recent merger activity (Coleman et al. 2004, Coleman & Da Costa 2005, Olszewski et al. 2006). Furthermore, results by Battaglia et al. (2006) suggest that the ancient stellar population in the centre of Fornax is not in equilibrium (apparent as a non-Gaussian, double peaked velocity distribution), which also points to a relatively recent accretion of external material, such as gas accretion due to the merger with another smaller stellar system.

2. Observations

All observations were carried out with the “Superb Seeing Imager”, SuSI2, attached to one of the Nasmyth foci of the ESO 3.5 m NTT telescope at La Silla Observatory in Chile. The overall characteristics of the detector are fully described in D’Odorico (1998) and D’Odorico et al. (1998). We followed exactly the same observational, reduction, and calibration procedures for all of our QSO fields as described in Paper I. Therefore, in as much as possible, our dataset is homogeneous from this point of view (for certain limitations to this statement, see Section 3). SuSI2 is a mosaic of two $2k \times 4k$ EEV 44-82 chips (called #45, on the West side, and # 46, on the East side, for the adopted rotator angle of 0°). As explained in Paper I, we always placed our QSOs at a nominal pixel position near $(x, y) = (3000, 2100)$, close to the middle of chip #46, and only data from this chip was subsequently used for our astrometry.

All of the astrometric observations, including those required to compute the differential chromatic constants (DCR - see Paper I, Section 3.3.), were acquired through a Bessel R filter, whereas for the blue frames needed to construct color-magnitude diagrams (CMDs) we used the Bessel B filter, both of which are part of the standard set of filters available for SuSI2.

Our initial list of QSOs in the background of Fornax comprised all eleven distinct QSOs (one, reported in Paper I, forms a gravitational lens

¹Another notable exception is the tidally disrupted Sagittarius dwarf which, along with Fornax, are the most massive of the MW satellite galaxies after the LMC and SMC. Sagittarius appears to have globular clusters that are, or were, associated with it (e.g., Law & Majewski 2010).

pair) reported by Tinney et al. (1997) (their Table 5) and Tinney (1999) (his Table 1). Unfortunately, several of them proved to be useless for astrometry: deep, good-seeing (FWHM \sim 0.5 arcsec) images taken during the first epoch revealed that they were either too faint for our required astrometric S/N (> 200 integrated over the PSF fitting radius; see Paper I, Section 3.2 and Figure 4), had a noticeably elongated structure (and therefore had a different, usually more extended, PSF than that of the stars), had a very nearby (usually stellar-like) bright companion, or were definitely blended with field stars. As explained at length in Paper I, any of these features render these targets unsuitable for high-accuracy relative astrometry. These problematic QSOs were dropped from the observing list in subsequent epochs, and we concentrated on “clean” (as far as we could determine with a seeing of \sim 0.5 arcsec) QSOs. Our final list of five QSOs, from which we were able to determine the PM of Fornax, is given in Table 1, where we also show the full list of known QSOs behind Fornax from the above-cited references.

In Figure 1 we show the stellar configuration in the immediate surroundings of each of our five selected QSOs. All of these images were acquired on the first epoch, when we consistently had very good seeing (FWHM \sim 0.5 arcsec). The only potentially problematic case was that of QJ0239-3420 which has a faint companion to the NW, at a distance of ~ 1.4 arcsec. Fortunately, this nearby source is very dim (with a Star/QSO peak brightness ratio smaller than 0.1), and far enough (farther than $1.2 \times FWHM$, adopted as the PSF fitting radius, see Paper I, Section 3.2 and Figure 4) that, even on our worse frames (with a FWHM of ~ 1.0 arcsec), it did not pose a problem for the astrometric solution, and so it was fully included in our analysis below.

Table 2 contains a summary of the observational material that was, in the end, used to compute our PMs. We note that more data was acquired for these QSO fields, but proved to be useless on account of bad seeing, poor image quality (deteriorating the astrometric solution), or bad sky transparency. As explained in Paper I, at the start of our program we adjusted the exposure time on the basis of seeing (typical values were between 300 s and 900 s), but later, it was decided to use a fixed integration time of 900 s in all

cases for simplicity.

3. Proper motions

To determine the PMs we used the same procedure described at length in Paper I. A flow-chart summary of the full process is presented in Figure 2. We refer the reader to Paper I for further details on the methodology and precise meaning of all steps. Even though in our PM solutions we only included frames acquired within ± 1.5 hr. from the meridian (see Table 2), all of our coordinates were (pre)-corrected for (continuous) atmospheric refraction and DCR as described in Paper I. We also excluded from the PM solution all frames with a $FWHM > 1.0$ arcsec, as they clearly deteriorated the linear fit of Baricentric position *vs.* epoch diagram (see, e.g., Fig. 12 in Paper I), where these frames stand-out due to their large scatter.

All PM data were treated as homogeneously as possible, including the following constraints:

- All stars with $\mu > 2.0$ mas y^{-1} in our initial local reference system (LRS, basically a set of “high-quality” reference stellar images, eventually bona-fide Fornax stars - see Paper I), indicating that they are either foreground Galactic stars, or that they have a high (pseudo)-PM, possibly due, e.g., to a faint unresolved companion or another problem in the image), were purged from the LRS. The full geometric registration (and PMs) for the remaining LRS stars and the QSO were re-computed in an iterative process,
- All LRS stars that exhibited a registration residual $\geq 3\sigma$ of the formal rms of the two-dimensional geometric registration in the X or Y coordinates in at least four (not necessarily consecutive) frames, were eliminated from the LRS. For registration we used a full 3^{rd} order polynomial fit, which has been justified in Paper I,
- All LRS stars with $\sigma_\mu > \sigma_{\mu_c}$ mas y^{-1} were excluded from the LRS. The cut value, σ_{μ_c} , was estimated for each field based on the distribution of PM errors *vs.* magnitude (see Table 3),

- LRS stars exhibiting a PM error larger than that of the bulk of the LRS stars at a given magnitude (even if they, individually, had $\sigma_\mu < \sigma_{\mu_c}$) were eliminated. This cut was done visually, on plots of PM error vs. magnitude for each QSO field,
- Finally, we expunged objects that in the CMD appeared not to belong to Fornax. This photometric cleansing was done by first calibrating our instrumental photometry following the procedure described in Paper I (Section 4), and then by comparing our resulting CMD with that of Stetson (1997), which defines the main features of the Fornax CMD.

In Table 3 we show a summary of what results from applying the above criteria to the initial set of LRS stars for each of our five QSO fields. After applying all previously described cuts, we verified that we ended with a uniform (X, Y) distribution of the LRS stars (see, e.g., Figure 15 in Paper I), and with a reasonable distribution in magnitude and color. The resulting CMDs for the LRS stars and the respective QSO are shown in Figure 3. We note that in Paper I we calibrated our photometry approximately by adopting a color of $(B - R) \sim 1.3$ for the red-clump from Stetson (1997) and the QSO blue magnitude from the works by Tinney et al. (1997) and Tinney (1999). However, we noticed that, probably as result of uncertainties in the blue photographic magnitudes for the QSOs (and/or possible QSO variability), the ordinate in these figures had a large zero-point variation from field to field, and hence the red-clump did not fall at the same apparent R magnitude for the five fields, as is expected. We therefore decided to adopt a calibration based on the color of the red-clump (as before), but fixing, instead, the magnitude of the red-clump at $R \sim 20.6$, also from the photometry by Stetson (1997, his Figure 7).

In Figures 4 and 5 we show, respectively, the barycentric position *vs.* epoch and the vector-point diagrams for our five fields, for the final LRS stars and the corresponding background QSO.

After processing all of the QSO fields following the protocols described in the previous paragraphs, we computed PMs for the five QSO fields presented in the upper part of Table 1. The re-

sults are summarized in Table 4, and are plotted in Figure 6. Table 4 gives the PM in RA and DEC as well as the overall rms of the linear fit of the barycentric coordinates *vs.* epoch. We recall that the slope of this linear fit gives us the PM of the Fornax stars with respect to the QSO, as explained in Paper I. Figure 6 clearly shows that our five measurements scatter more widely than would be expected from their error bars, and therefore computing a weighted mean does not seem appropriate for these data. Instead, and not knowing the source of the additional uncertainty affecting our proper motion measurements, we opted for computing an unweighted mean over the resulting values for all five QSO fields. From Table 4 we thus arrive at the following values for the PM of the Fornax dSph galaxy (and the standard deviation of the mean): $\mu_\alpha \cos \delta = 0.62 \pm 0.16$ mas y^{-1} , and $\mu_\delta = -0.53 \pm 0.15$ mas y^{-1} .

3.1. Comparison to other studies

Only two astrometric determinations of the PM for the Fornax dSph galaxy are available, namely that by Dinescu et al. (2004), based on a combination of ground-based plates and Hubble-WFPC data, and that based exclusively on HST data by Piatek et al. (2007, hereafter PI07), who present revised values to those reported earlier (pre-CCD Charge Transfer Inefficiency corrections) in Piatek et al. (2002).

Figure 6 compares our results from individual QSOs, to those obtained by PI07. We have three QSO fields in common with PI07; their values, along with our measurements, are given in Table 5. From this Table we see that the difference of the mean PMs derived from the QSOs in common between these two studies is less than 1σ of our error in the mean in both, RA and DEC. On the other hand, the overall weighted mean value reported by PI07, based on 4 QSOs (their Table 3) of $\mu_\alpha \cos \delta = 0.476 \pm 0.046$ mas y^{-1} , and $\mu_\delta = -0.360 \pm 0.041$ mas y^{-1} differs by about 1σ from our overall unweighted-mean PM values. Even though our results are not statistically inconsistent with those of PI07, it is apparent from Figure 6 that our individual results do exhibit a much larger scatter than their results ($\sigma_{\mu_\alpha \cos \delta} = 0.36$ mas y^{-1} and $\sigma_{\mu_\delta} = 0.34$ mas y^{-1} vs. $\sigma_{\mu_\alpha \cos \delta} = 0.06$ mas y^{-1} and $\sigma_{\mu_\delta} = 0.09$ mas y^{-1} for PI07). We have no expla-

nation for these differences.

The PM values published so far, along with our own value are given in Table 6. More recently, Walker et al. (2008) have used a non-astrometric method called “perspective rotation” which is also included in the table (for details about this method see Paper I), because it provides a completely independent measurement of the tranverse motion of Fornax (albeit with a larger error than the more recent astrometric determinations). All of these values are plotted, for comparison, in Figure 7. From the plot and figure we can see that, in general, there is a good agreement between all measurements; indeed, none of them depart by more than 2σ from the straight average of the values in Table 6, with our result being however the most extreme in this sense. Also, averaging the results from all of the authors, we find that the PM in DEC shows a larger scatter ($\sigma_{\mu_\delta} = 0.16 \text{ mas y}^{-1}$) than that in RA ($\sigma_{\mu_\alpha \cos \delta} = 0.064 \text{ mas y}^{-1}$). This would suggest that (some of) these measurements are affected by unaccounted systematic effects. Of the obvious culprits, we can mention that ground-based astrometric data are affected by DCR. In the case of Fornax data (DEC $\sim -34^\circ$) acquired from the Southern Hemisphere, DCR should however mostly affect RA PMs (we stress that our data have been corrected for this effect as far as possible, see Paper I).

On the other hand, HST data, while not affected by DCR, can be affected by “Charge Transfer Inefficiency” (CTI) in the CCD detectors due to the very low sky background which is insufficient to fill-in the empty charge traps on the detector. These traps evolve in time because they are produced by in-flight radiation damage, and induce systematic (time dependent) position shifts in the detected sources (for details see, e.g., Bristow et al. (2006), especially his Figure 10). HST data has also been corrected for this effect, again, as best as they could (compare, e.g., Table 3 from Piatek et al. (2002) (CTI-uncorrected) and PI07 (CTI-corrected)). We note however that, since the HST cameras were not oriented exactly along DEC in the parallel readout direction, which is the direction mostly affected by CTI (see, e.g., Figures 2, 3 and 4 in PI07), it is difficult to ascribe the DEC scatter to this problem. Also, as mentioned previously, HST data shows a much

smaller intrinsic scatter than our measurements (Figure 6), thus suggesting small remaining systematics due to CTI.

4. Discussion and outlook

One of the ultimate goals of these studies is a determination of a reliable orbit for Fornax. It is interesting to compare the impact of the different values given in Table 6 on the kinematical and orbital parameters that can be derived from these measurements. Table 7 gives the Heliocentric PMs and the corresponding tangential velocities in Galactic coordinates for the different values reported in Table 6. From this table, it is clear that our PM value will render one of the most energetic orbits yet derived for Fornax.

For illustration purposes, and also as a key ingredient to compute and interpret the orbit of Fornax from the above motions in Galactic coordinates, we have computed velocities in the Heliocentric (HC) and Galactocentric (GC) reference systems. For a detailed description of these various reference systems, and the equations relating them, the reader is referred to Costa et al. (2009). They are shown in Table 8, along with model-independent kinematical and orbital parameters derived from the PM values taken from different studies. Given the large values of $V_{t_{GC}}$ in comparison with the $V_{r_{GC}}$ derived from all PM measurements, it is clear that Fornax must be close to perigalacticon at this time. Also, given the rather small ratio of L_z/L it is clear that there must be significant excursions of Fornax away from the Galactic plane, regardless of the adopted PM values. We note again that, of all measurements available, our PM measurement yields the most extreme orbit.

We have computed Galactic orbits for Fornax by integrating back in time the equation of motion under a realistic three-component (disk, halo and spheroid) model Galactic potential (Johnston et al. 1995), and using the current position and velocity (and their uncertainties, in a Monte Carlo scheme) as initial conditions. Details of the integrator, and the Monte Carlo simulations, are discussed in Dinescu et al. (2004). A particularly important feature of the integrator used is its care to conserve energy and total angular momentum, obvious features that are however sometimes tricky to achieve over the

full orbit, particularly when the number of integration steps (\sim several thousands in our case) is large. The adopted gravitational potential is strictly axi-symmetric, and it does not include the Galactic bar, nor the MW spiral pattern. Recent numerical simulations by Allen et al. (2008), that include these non axi-symmetric components, indicate however that their effect, in particular in the orbits of Galactic globular clusters (and therefore also in the case of the more external satellite galaxies), is minimal, and it should not alter our conclusions importantly. The results of these integrations are shown in Table 9 and in Figure 8. In Table 9 the meaning of the different columns is rather obvious, except perhaps for the last two columns that correspond to the crossing (vertical) velocity of Fornax through the Galactic plane (V_z) and the total speed at perigalacticon (V_p). As it can be seen, regardless of what PM values one adopts, comparing the V_p values to the $V_{t_{GC}}$ in Table 8 confirms that the current Fornax position lies indeed near perigalacticon (see also Figure 9, top panel). Actually, all PMs indicate that the minimum distance, projected into the Galactic plane, happened 200 to 300 Myr ago (Figure 9, bottom panel). This is a very interesting quantity, because Battaglia et al. (2006) have found evidence of at least three distinct stellar components in Fornax: a young population (few 100 Myr old) concentrated in the centre of the galaxy, visible as a Main Sequence in the CMD; an intermediate age population (2-8 Gyr old, possibly related to a shell structure in Fornax, described in the next paragraph); and an ancient population (> 10 Gyr). More recently, Kirby et al. (2011) have also found (see, e.g., their Figure 2) evidence of enhanced star formation in the range 200-300 Myr. One could therefore conclude that the latest episode of star formation on Fornax may have been indeed triggered by its perigalacticon passage.

When tracing the galaxy back in time, the uncertainty in the computed position increases as time goes on, for a given uncertainty in the initial conditions, and, as we extrapolate further back in time, different PM values lead to quite different orbits. This is clearly shown in Figure 9, which shows the distance of Fornax from the Galactic center (d_{GC} , top panel) and the same distance projected onto the Galactic plane (R_{pl} , bottom panel) as a function of time from now. Initially

all PM values produce a similar d_{GC} , R_{pl} *vs.* time, but the solutions diverge afterwards. As mentioned before, our value renders the most extreme solution, basically indicating that in a Hubble time Fornax has not completed an orbit yet. This is at odds with all of the other solutions which, while being different among themselves, do indicate nevertheless several perigalacticon passages in the last 10 Gyr. If, as argued before, perigalacticon has had an influence on enhancing star formation, the stellar population results by Battaglia et al. (2006) favour a rather long orbital period, thus supporting our solution. We note here that the 2 Gyr population belonging to the shell structure found by Coleman et al. (2004), Coleman & Da Costa (2005), and Olszewski et al. (2006) has been interpreted by these authors as the product of a merger with a smaller, gas-rich system, and may not bear any relation to the interaction between Fornax and the MW. We are thus seemingly left with two significant star formation episodes, one at (200-300 Myr), close to perigalacticon, and another one at age > 10 Gyr, which again argues for a longer orbital period (interestingly, from Figure 9 we see that ~ 2 Gyr mark the most recent apogalactic position for Fornax for the PI07 and Walker et al. (2008) orbits). Our extended orbit implies that Fornax would belong to one of the “hypervelocity” satellites of the MW, as argued by Kallivayalil et al. (2006), Besla et al. (2007), Piatek et al. (2008) (results all based on the same HST data set). One could perhaps wonder that the late infall nature of Fornax’s orbits (assuming our PMs) is possibly related to the fact that it is the only satellite dwarf galaxy of the MW (Mateo 1998), along with the spatially dissipated Sagittarius dwarf (Law & Majewski 2010), that harbour a globular cluster population.

A final word of caution regarding the above discussion is that, from Table 9, we see that current PM measurements for Fornax implies that the range of derived orbital parameters is quite broad, and it seems adventurous to extract strong conclusions from them. As already mentioned, of particular concern is the possible existence of yet unaccounted systematic effects in the PM measurements. Only high-accuracy future astrometric satellite measurements, like GAIA, with expected uncertainties of a few μ arc-sec (average over many stars) could help resolve this issue.

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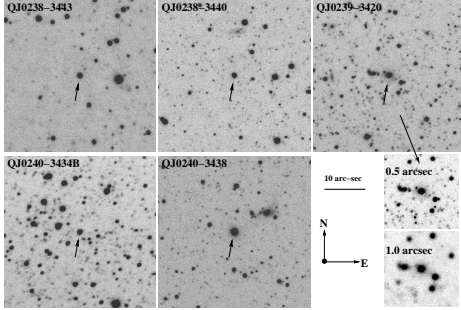


Fig. 1.— Finding charts indicating the configuration and surroundings of our five QSO fields. The QSOs are indicated by an arrow. The field-of-view is ± 250 pix around the QSO (approximately 40 arcsec on a side), and the FWHM of all images is ~ 0.5 arcsec. With the exception of QJ0239-3420, all QSOs are well isolated from surrounding sources (see text). Our tests indicate that the small source to the NW of QJ0239-3420 does not affect the astrometry. To illustrate the effect of seeing, in the bottom right inset, we show a zoom of the area around QJ0239-3420 for best (top) and worse (bottom) FWHM frames for this field.

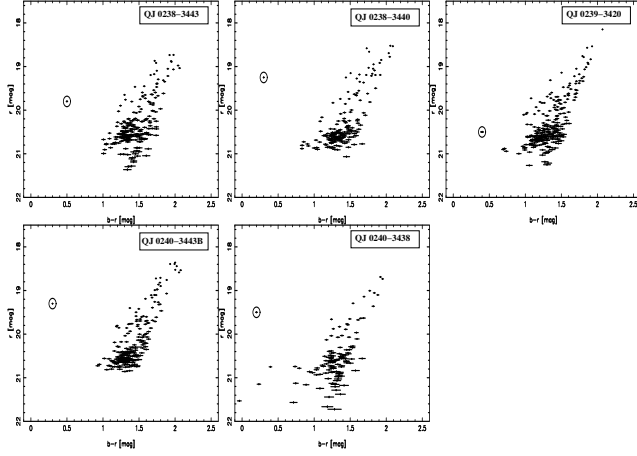


Fig. 3.— *Instrumental* CMDs for our five QSO fields. The QSO is indicated by an ellipse. For comparison purposes among the different fields, our PSF photometry has been *approximately* calibrated by adopting a red-clump magnitude and color of $R \sim 20.6$ and $(B - R) \sim 1.3$ respectively (from Stetson 1997).

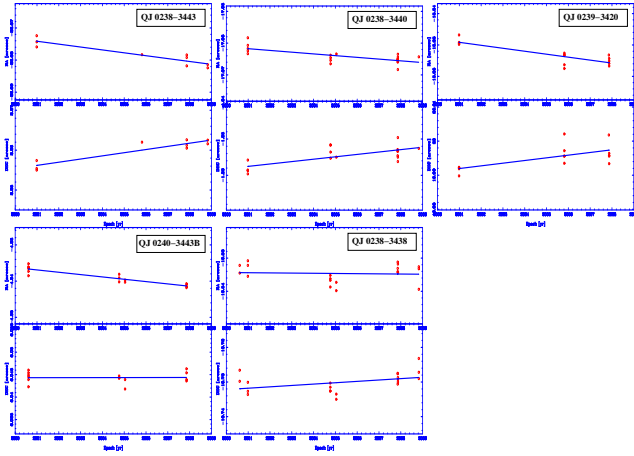


Fig. 4.— QSO barycentric position with respect to the (final) LRS stars *vs.* epoch for our five QSO fields. The lines are (unweighted) fits to the data points, and the negative of the slope of these fits corresponds to the PM of Fornax, whose values are tabulated in Table 4.

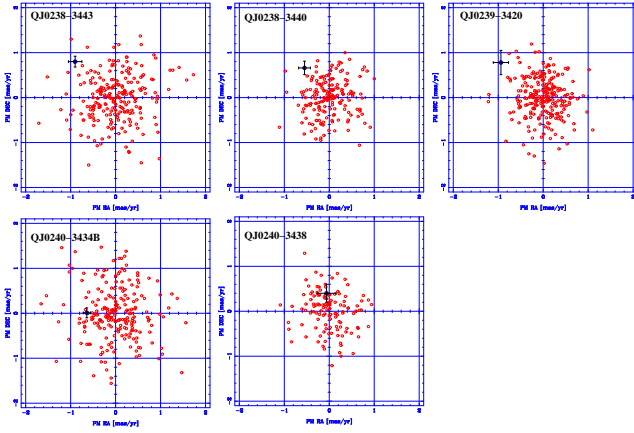


Fig. 5.— Vector-point diagrams for our five QSO fields, after having applied the selection criteria described in the text. The QSO is indicated by a solid dot with error bars (1σ uncertainty on the slope of the barycentric position *vs.* epoch fit). The (pseudo-) PM error of individual LRS stars is similar to that of the QSO, so the mean motion of the bulk of the LRS stars has a very small uncertainty, and our final error is dominated by the PM uncertainty of the QSO itself (see Costa et al. 2011).

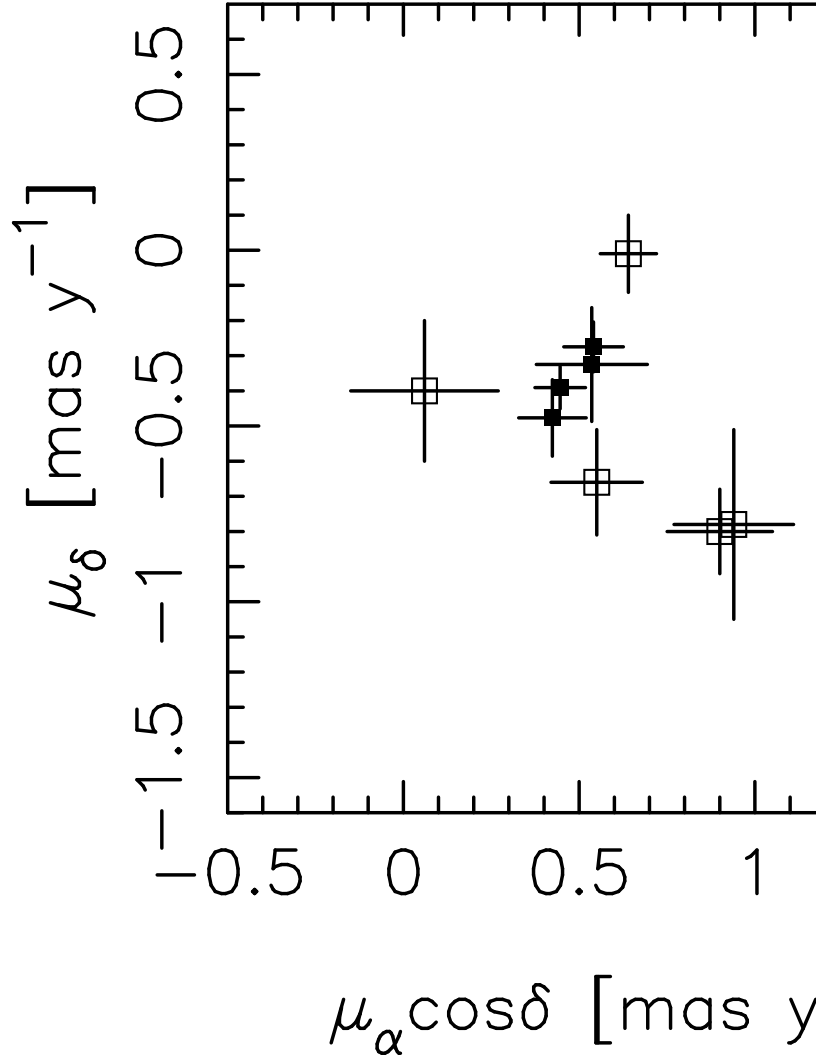


Fig. 6.— Individual Fornax PMs determined from our five QSO fields (from Table 4, open squares). Filled squares are the HST PC2+STIS results from four QSOs by Piatek et al. 2007, their Table 3. Three of these QSOs are common to ours (see our Table 5).

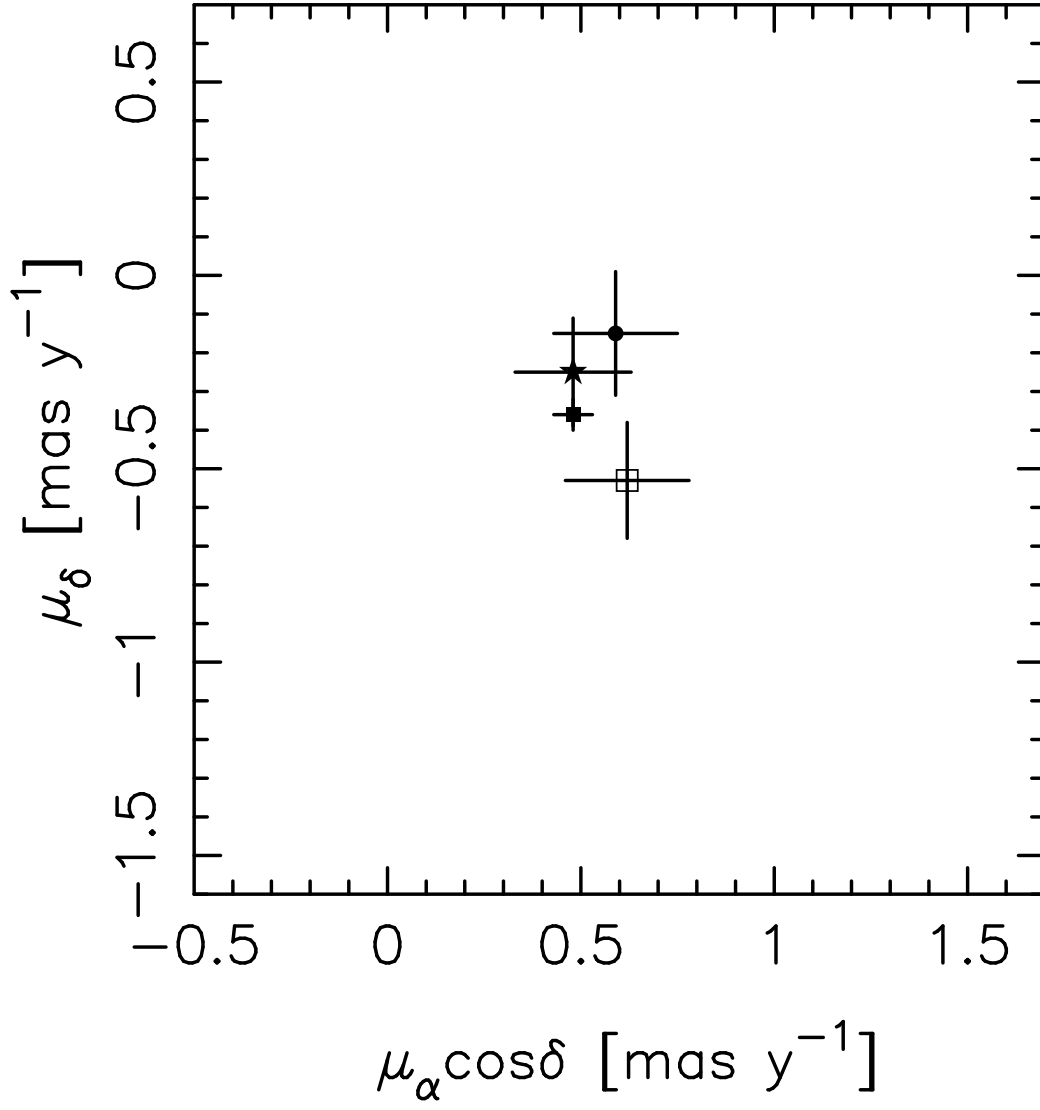


Fig. 7.— Mean Fornax PM and their 1σ errors as determined by various authors: Filled dot from Dinescu et al. (2004), filled square from Piatek et al. (2007), filled star from Walker et al. (2008), and open square this work (see Table 6).

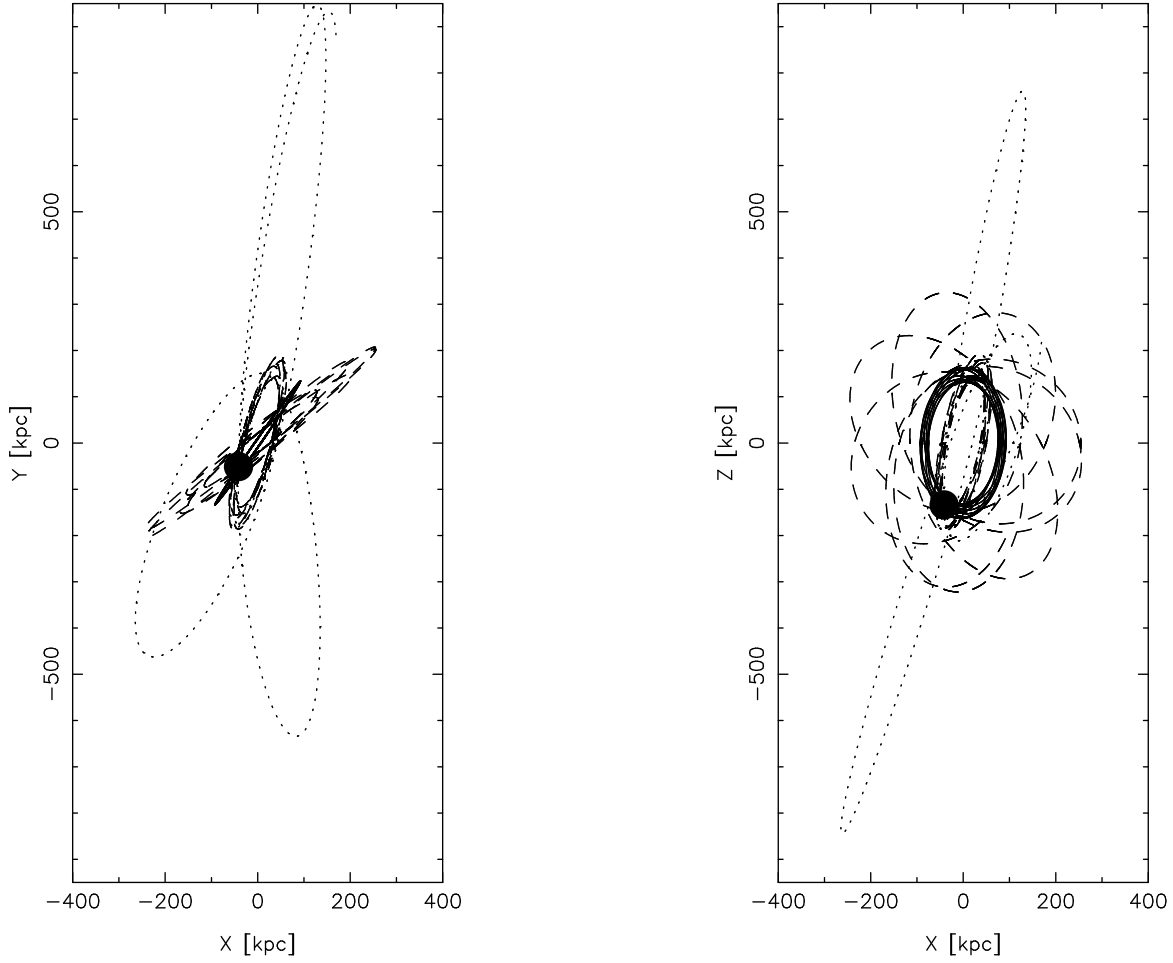


Fig. 8.— X-Y and X-Z projections of the orbit for Fornax from PM values by different authors: Dashed line is Dinescu et al. (2004), dot-dashed Piatek et al. (2007), full line Walker et al. (2008), and dotted line this work. The filled dot at $(X, Y, Z) = (-41.4, -50.9, -133.9)$ kpc indicates the current position of Fornax.

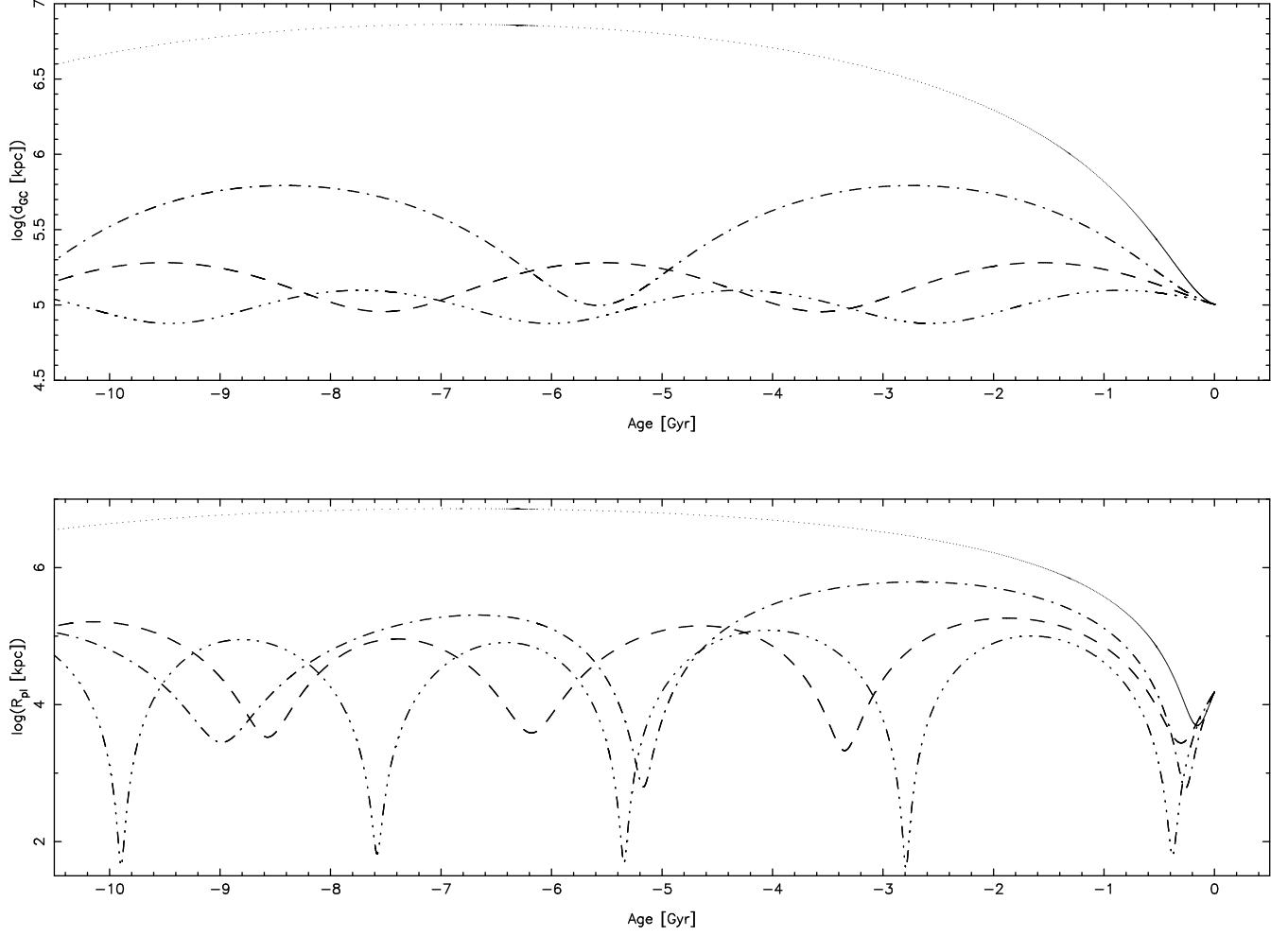


Fig. 9.— Fornax distance (log scale) as a function of age from our orbit integrations, for PM values from different authors. Top panel is for the Galactocentric distance, bottom panel is for the distance projected on the plane of the MW. Both panels: Dot-dashed line is for Dinescu et al. (2004), dashed line for Piatek et al. (2007), double dot-dashed line for Walker et al. (2008), and dotted line for this work.

TABLE 1
QSOs IN THE BACKGROUND OF FORNAX, FROM TINNEY ET AL. (1997) AND TINNEY (1999), IN ORDER
OF INCREASING RA^a.

QSO ID	RA (J2000) [hh:mm:ss.s]	DEC [⁰ : ['] : ^{''}]	B [mag]	ρ^b [arcmin]	θ^b [deg]	Comments
QJ0238-3443	02:38:43.8	-34:43:53	20.2	22.9	222	
QJ0238-3440	02:38:55.6	-34:40:45	20.1	19.0	223	
QJ0239-3420	02:39:49.0	-34:20:00	20.6	07.3	344	
QJ0240-3434B	02:40:08.2 ^c	-34:34:22 ^c	19.9	07.6	166	Reported in Paper I
QJ0240-3438	02:40:38.7	-34:38:58	20.2	14.5	146	
QJ0239-3425	02:39:32.9	-34:25:25	20.4	—	—	No finding chart available
QJ0239-3421	02:39:36.9	-34:21:30	19.9	—	—	Fuzzy, elongated QSO image, with a FWHM 48% larger than that of stars in the FOV
QJ0240-3434A	02:40:07.7 ^d	-34:34:20 ^d	19.1	—	—	Blended to foreground star
QJ0240-3437	02:40:19.0	-34:37:20	17.9	—	—	QSO exhibits complex structure
QJ0241-3420	02:41:57.9	-34:20:49	20.4	—	—	No finding chart available, far from Fornax's center
QJ0242-3426	02:42:06.5	-34:26:12	21.8	—	—	Faint and far from Fornax's center
QJ0242-3424	02:42:19.9	-34:24:20	21.5	—	—	Faint and far from Fornax's center

^aThe upper part of the table shows the QSOs used in this work. The bottom part indicates those which could not be used for astrometric purposes or were otherwise discarded for various reasons, as indicated under column “Comments”.

^bTo compute the angular distance (ρ) and position angle (θ) of the QSO with respect to Fornax, we have taken the J2000 coordinates for the center of Fornax from Table 1 of Mateo (1998), namely RA=02:39:59, and DEC=-34:27.0. We note that these values differ by more than 1 arcmin in RA and 3 arcmin in DEC from the values presented in the review of LG galaxies by van den Bergh (1999, Table 1) which, given the low surface brightness (~ 23.4 mag arcsec⁻² in the V band) and large angular extent (a core radius of 14 arcmin) of the galaxy (Mateo 1998), is probably understandable.

^cAccording to Tinney et al. (1997) component B is 5.9 arcsec East and 1.6 arcsec S of component A, whose coordinates are given in ^d. In our images we measure similar offset values for component B, namely, 5.8 arcsec East and 1.4 arcsec S from component A.

TABLE 2
ASTROMETRIC R-BAND^a FRAMES *effectively* USED IN EACH OF OUR FIVE QSO FIELDS.

QSO ID	Epoch range [year]	# epochs	# astrometric frames ^b	# DCR frames	DCR HA range [hour]
QJ0238-3443	2000.98 ... 2008.82	4	09	09	0.68 ... 2.99
QJ0238-3440	2000.98 ... 2008.82	4	19	13	0.36 ... 3.86
QJ0239-3420	2000.99 ... 2007.87	3	14	12	0.55 ... 3.70
QJ0240-3434B ^c	2000.61 ... 2007.85	3	15	13	-0.65 ... -4.03
QJ0240-3438	2000.61 ... 2008.83	4	20	10	-0.74 ... -3.62

^aAs explained in the text, B-band frames for building up CMDs of each field were also acquired.

^bAll of these frames satisfy that $|HA| \leq 1.5$ hr, and $FWHM \leq 1.0$ arcsec (as an example, see Table 1 of Paper I).

^cReported in Paper I.

TABLE 3
LOCAL REFERENCE STARS AND CUTS APPLIED IN EACH QSO FIELD.

QSO ID	# initial LRS stars	# final LRS stars	σ_{μ_c} [mas y ⁻¹]	PM error vs. mag # stars purged	CMD cleansing # stars purged
QJ0238-3443	295	226	0.78	3	12
QJ0238-3440	217	175	0.60	6	7
QJ0239-3420	337	250	0.60	12	11
QJ0240-3434B	260	217	0.50	11	7
QJ0240-3438	156	123	0.60	0	9

Table 4: Fornax PM from our five QSO fields.

QSO ID	$\mu_\alpha \cos \delta$ [mas y ⁻¹]	μ_δ [mas y ⁻¹]	σ_{fit} in RA [mas]	σ_{fit} in DEC [mas]
QJ0238-3443	0.90 ± 0.15	-0.80 ± 0.12	1.5	1.2
QJ0238-3440	0.55 ± 0.13	-0.66 ± 0.15	1.6	2.0
QJ0239-3420	0.94 ± 0.17	-0.78 ± 0.27	1.8	2.8
QJ0240-3434B	0.64 ± 0.08	-0.01 ± 0.11	0.9	1.3
QJ0240-3438	0.06 ± 0.21	-0.40 ± 0.20	2.8	2.7
Unweighted mean	0.62 ± 0.16	-0.53 ± 0.15	–	–

Table 5: Comparison of Fornax PMs derived by Piatek et al. (2007) with our results *for the same* QSO fields.

QSO ID	$\mu_\alpha \cos \delta$	μ_δ	$\mu_\alpha \cos \delta$	μ_δ
	[mas y ⁻¹]	[mas y ⁻¹]	[mas y ⁻¹]	[mas y ⁻¹]
	Piatek et al. (2007)		This work	
QJ0238-3443	0.45 ± 0.07	-0.39 ± 0.06	0.90 ± 0.15	-0.80 ± 0.12
QJ0240-3434B	0.42 ± 0.10	-0.48 ± 0.11	0.64 ± 0.08	-0.01 ± 0.11
QJ0240-3438	0.54 ± 0.16	-0.33 ± 0.16	0.06 ± 0.21	-0.40 ± 0.20
Unweighted mean	0.47	-0.40	0.53	-0.40

TABLE 6
PUBLISHED MEAN FORNAX PMS AND THEIR UNCERTAINTIES.

Reference	$\mu_\alpha \cos \delta$ [mas y ⁻¹]	μ_δ [mas y ⁻¹]	PM [mas y ⁻¹]	PA ^a [deg]	Comments
Dinescu et al. (2004)	0.59 ± 0.16	-0.15 ± 0.16	0.61 ± 0.16	104 ± 15	Plates, 48 galaxies and 8 QSOs
Piatek et al. (2007)	0.476 ± 0.046	-0.360 ± 0.041	0.597 ± 0.044	127 ± 4	HST+PC2+STIS, 4 QSO fields
This work	0.62 ± 0.16	-0.53 ± 0.15	0.82 ± 0.16	125 ± 11	NTT+SuSI2, 5 QSO fields
Walker et al. (2008)	0.48 ± 0.15	-0.25 ± 0.14	0.54 ± 0.15	118 ± 15	Radial velocities, “perspective rotation”

^aPosition angle measured from North to East.

Table 7: Proper motions in the Galactic coordinate system^a and tangential velocities^b derived from the PMs given in Table 6.

Reference	μ_l [mas y ⁻¹]	μ_b [mas y ⁻¹]	V_l [km s ⁻¹]	V_b [km s ⁻¹]	V_t [km s ⁻¹]
Dinescu et al. (2004)	0.04 ± 0.16	0.60 ± 0.16	31 ± 112	423 ± 112	424 ± 112
Piatek et al. (2007)	0.271 ± 0.041	0.532 ± 0.046	189 ± 31	370 ± 34	416 ± 33
This work	0.41 ± 0.15	0.70 ± 0.16	288 ± 107	490 ± 113	568 ± 112
Walker et al. (2008)	0.16 ± 0.14	0.52 ± 0.15	113 ± 98	360 ± 105	377 ± 104

^aTo derive Galactic motions from the J2000 $\mu_\alpha \cos \delta$ and μ_δ PMs we have adopted a position for the J2000 Galactic Pole of RA=(12:51:26.2754, DEC= +27:07:41.705) following Miyamoto & Soma (1993) (see, especially, their equation (29)).

^bTo derive the tangential velocities V_l and V_b , we have adopted a distance modulus for Fornax of $(m-M)_0 = 20.84 \pm 0.15$ from the “Araucaria distance scale project” (Pietrzyński et al. 2009). The velocity values above include a full statistical propagation of PM and distance (taken to be $d = 147 \pm 10$ kpc) errors. V_t is the total Heliocentric tangential velocity, and its error.

TABLE 8
FORNAX CURRENT HELIOCENTRIC^a AND GALACTOCENTRIC^b VELOCITIES AND SPECIFIC ORBITAL
KINEMATICAL PARAMETERS FROM VALUES OF DIFFERENT AUTHORS.

Reference	U_{HC} [km s ⁻¹]	V_{HC} [km s ⁻¹]	W_{HC} [km s ⁻¹]	$V_{r\text{GC}}$ [km s ⁻¹]	$V_{t\text{GC}}$ [km s ⁻¹]	$V_{b\text{GC}}$ [km s ⁻¹]	$V_{l\text{GC}}$ [km s ⁻¹]	K/m^c [$\times 10^3$ (km s ⁻¹) ²]	L/m^d [$\times 10^3$ kpc km s ⁻¹]	L_z/m^d [$\times 10^3$ kpc km s ⁻¹]
Dinescu et al. (2004)	-195 ± 109	-359 ± 105	126 ± 46	-23 ± 62	59 ± 107	257 ± 98	263 ± 98	35	38	-3.9
Piatek et al. (2007)	-36 ± 31	-404 ± 31	104 ± 15	-32 ± 19	-93 ± 32	189 ± 29	210 ± 30	23	31	6.1
This work	-13 ± 106	-550 ± 104	154 ± 47	-33 ± 62	-203 ± 105	298 ± 96	361 ± 99	66	53	13.3
Walker et al. (2008)	-95 ± 97	-355 ± 96	100 ± 43	-28 ± 58	-16 ± 97	186 ± 89	186 ± 89	18	27	1.1

^aHeliocentric velocities have been computed using the adopted J2000 RA and DEC coordinates for the Fornax center (see Table 7), which correspond to Galactic coordinates $(l, b) = (237.10^\circ, -65.65^\circ)$. The errors correspond to the statistical propagation of all observational errors. The (U, V, W) is a right-handed system that points to the Galactic center, Galactic rotation and North Galactic Pole respectively.

^bGalactocentric velocities have been computed adopting a solar peculiar velocity of $(u_\odot, v_\odot, w_\odot) = (10.00 \pm 0.36, 5.25 \pm 0.62, 7.17 \pm 0.38)$ km s⁻¹ from Dehnen & Binney (1998), a LSR speed of 220 ± 5 km s⁻¹ and $R_\odot = 8.5 \pm 0.5$ kpc. The errors correspond to the statistical propagation of all observational errors. While these are commonly used values, we note that recent studies seem to suggest a larger V-component of the solar motion with respect to the LSR, ~ 13 km s⁻¹ (e.g., Coşkunoğlu et al. 2011). However, given the current PM uncertainties, this change will have little effect on the calculated motion of Fornax. Also, note that our uncertainty for the LSR speed is rather optimistic, for example, Bovy et al. (2009) quote $V_{\text{LSR}} = 244 \pm 13$ km s⁻¹, while Brunthaler et al. (2011) argue for $V_{\text{LSR}} = 239 \pm 7$ km s⁻¹.

^cKinetic energy per unit mass, as seen from a point at rest with respect to the Galactic Center.

^dTotal $(=\sqrt{L_x^2 + L_y^2 + L_z^2})$ and z-component of the angular momentum per unit mass, with respect to the Galactic Center, in our right-handed system.

TABLE 9
FORNAX ORBITAL PARAMETERS FROM PM VALUES OF DIFFERENT AUTHORS^a .

Reference	Orbital period [Gyr]	Apogalactic distance [kpc]	Perigalactic distance [kpc]	Z_{max} [kpc]	Z_{min} [kpc]	Excentricity	Inclination [deg]	V_Z [km s ⁻¹]	V_p [km s ⁻¹]
Dinescu et al. (2004)	8 ± 4	328 ± 226	148 ± 10	223 ± 84	-238 ± 108	0.38 ± 0.21	68 ± 8	189 ± 9	265 ± 51
Piatek et al. (2007)	6 ± 1	197 ± 58	142 ± 14	163 ± 35	-166 ± 37	0.16 ± 0.09	76 ± 4	186 ± 2	221 ± 17
This work	21 ± 8	956 ± 376	148 ± 8	498 ± 191	-411 ± 172	0.73 ± 0.18	41 ± 8	181 ± 19	363 ± 51
Walker et al. (2008)	5 ± 3	164 ± 109	131 ± 30	147 ± 73	-148 ± 66	0.11 ± 0.18	83 ± 7	191 ± 8	212 ± 41

^aThe errors were computed as the inner 50% interquartile range derived from 1,000 simulations with uncertainties drawn from Gaussian distributions of the errors in PMs, V_r , and distance. The integration period was chosen to be large enough (50 Gyr) so that the longest orbital period solution completed at least two full orbital cycles.